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A NEW METHOD OF LOCATING SOURCES OF ACOUSTIC RADIATION IN THREE-DIMENSIONAL SPACE

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1. INTRODUCTION

This paper outlines a new method of locating sources of acoustic radiation by means of multi-microphone arrays of arbitrary shape. Furthermore, the location of each microphone does not need to be known precisely. Sources are located by the method of optimal phase binning, a process which will be described below. This method constructs a frequency spectrum faster than the fast Fourier transform. In addition, optimal phase binning determines the locations of sources in three-dimensional space. Furthermore, optimal phase binning can be used equally effectively with samples taken at regular intervals in space and time. Finally, the method can be used equally effectively if the locations of the microphones are known exactly.

2. THE METHOD OF OPTIMAL PHASE BINNING

2.1 Convolution of Samples Taken at an Instant in Time

Sensors placed at arbitrary positions in three-dimensional space are used to pin-point the locations of sources of acoustic radiation at an instant in time. At a given instant, an acoustic pressure measurement is captured from each sensor. Then, all of these measurements are convolved with each other in optimal phase binning procedure, to be outlined below, in order to locate each source.

Frequencies are measured at each location. The positions of power maxima are the true locations of the sources.

2.2 Phase Binning

A test cycle of given length is divided into phase intervals, each of equal length. A phase bin is an interval of a fraction of a cycle. The phase bins are of equal length. Starting at an arbitrary point in the test cycle, samples of acoustic radiation worked out to be in the first subinterval of the cycle are placed in the first bin. Samples worked out to be in the second subinterval of the cycle are placed in the second bin, and so on.

2.3 Optimal Phase Binning

With optimal phase binning, a test cycle of given length is divided into three phase intervals, each of equal length. A phase bin of optimal size is an interval of one third of a cycle. The three bins are of equal length. Thus the width of each bin is one third of the cycle of interest. Starting at an arbitrary point in the test cycle, samples of acoustic radiation worked out to be in the first third of the cycle are placed in the first bin. Samples worked out to be in the second third of the cycle are placed in the second bin. Finally, samples worked out to be in the last third of the cycle of interest are placed in the third bin.

It can be shown that three is the smallest possible number of bins. It can also be shown that noise is treated most effectively with three bins. Furthermore, the division of the cycle into three bins, rather than some other integer number of bins, enables the construction of a power integral without having to carry out convolution for all possible phase angles of the test cycle.

2.3 Optimal Phase Binning Procedure

If the test cycle is a frequency component of the acoustic radiation sampled, then the pressure measurements taken from all the sensors will tend to reinforce one another in each bin. But if the measured pressures cancel each other out, then a test cycle of that frequency is not present in the signal.

2.4 Computation of the Power Integral

First, the average of the measured acoustic pressures in each bin is computed. Then, each of the three averages is squared. Finally, the optimal binning power integral is constructed by adding these three squared averages together. The optimal binning power integral is large if the frequency of the test cycle is present in the acoustic radiation. But the integral is small if the frequency of that test cycle is not present. Furthermore, the optimal binning power integral will be greatest if the test location is at the true location of the source. It can be shown analytically that the square of the amplitude of the source is directly proportional to the optimal binning power integral.

2.5 Optimal Number of Bins for Noise Rejection

It can be shown that in order to treat noise as effectively as possible, the ratio of the optimal binning power integral and the square of the amplitude is best kept as small as possible. This is achieved when three bins are used. Three is the smallest possible number of bins.

3. DISCUSSION

3.1 Comparison with Fourier Methods

There is no theoretical basis for constructing a Fourier integral with samples taken at wildly irregular intervals. This method is therefore invalid for cases where sensors are not placed in locations that allow the acoustic radiation to be sampled at regular intervals at an instant in time. But the method of optimal phase binning is effective for locating sources with samples taken at irregular intervals. In particular, optimal phase binning is effective for tracking sources of acoustic radiation which are moving.

Furthermore, the construction of Fourier integrals involves comparing the magnitude of the integrals with all possible phase angles. It can be shown that the integral of the greatest magnitude is constructed when a cycle of the test frequency is in phase with one of the frequencies of the acoustic radiation. However, as the test cycle is shifted out of phase with the true frequency, so the magnitude of the Fourier integral diminishes. Finally, the integral is smallest when the two cycles are one quarter of a cycle out of phase with one another. But with the method of optimal phase binning, the division of the cycle can be started at any point in the cycle. It can be shown analytically that the optimal binning power integral has the same magnitude regardless of the starting point in the cycle. This means that the optimal phase binning power integral can be constructed faster than a Fourier integral.

With a Fourier integral, each sample is multiplied by a suitable number generated by the computer for the particular frequency of interest. But with the optimal power binning integral, the samples are simply added together, and the sum divided by the number of samples. This too means that the method of optimal phase binning is faster than Fourier methods.

With a Fourier integral, values in a look-up table are used to generate sinusoidal convolution values. But such values cannot be generated to arbitrary precision. Furthermore, the theoretical basis of the Fourier integral requires that there be a full complement of phase angle values for a cycle of the frequency of interest. In other words, the Fourier integral cannot be construed with samples taken at irregular intervals. But with the method of optimal phase binning, the only numbers requiring to be generated by the computer are the cycle lengths and their third and two third fractions. In particular, with the Fourier integral, numbers need to be generated for every sample taken. Moreover, the theory of the Fourier integral requires that the samples be integrated in strict order of phase angle. But this is not necessary with the method of optimal phase binning. With optimal phase binning, the samples in each bin are added together regardless of which phase angle they refer to. To sum up, the method of optimal phase binning requires a very much smaller number of convolution numbers than does the Fourier integral.

The fast Fourier transform takes advantage of the susceptibility to aliasing of the Fourier transform. But the method of optimal phase binning avoids these aliases. In particular, the method of optimal phase binning avoids frequency aliases which are integer multiples of true frequencies.

The theoretical basis of the Fourier integral requires that samples be taken at regular intervals. If, however, there is uncertainty about where or when the samples were taken, the Fourier method is invalid. But with the method of optimal phase binning, some uncertainty is accommodated because the integral can be constructed without the samples having to be assigned to a particular bin or convolved in a particular order. In other words, it is sufficient with optimal phase binning to assign a particular sample to a bin rather than to a particular phase angle.

4. EXAMPLE

4.1 Recording an Orchestra

Suppose an orchestral performance is to be recorded. For post-performance signal analysis and processing, it is argued by the foregoing theory that it is best to place the microphones so that each group of instruments is equidistant from each microphone. The reason for this is that it is easier to distinguish the powers of the different sources if the sources are equidistant from each microphone. In particular, it is easier to calculate the intrinsic amplitude of each source if the distances between the sources and sensors are all the same. In the language of linear algebra, it can be difficult to calculate the smaller eigenvalues accurately because of ill-conditioning. Such a case arises, for instance, when a microphone is placed right up against a particular source. The signal captured by such a microphone will be dominated by one strong frequency component. At the same time, however, the same microphone will pick up the frequencies of the other instruments. But these other frequencies will be captured with very much smaller power. In the language of linear algebra, this means that the data contain one large eigenvalue and other very much smaller ones, which may be difficult to determine. This outcome is avoided if all of the microphones are placed equidistantly from the various groups of orchestral instruments.

If it is necessary, for example, to alter the output of a particular voice after the recording has been made, this can be achieved more easily if the voices can be distinguished by their locations.

Microphone arrays should be disposed so as to allow the broadest possible baseline. This is in order to increase the angle of parallax between the sensors and the sources. The greater the angle of parallax, the easier it is to determine the location of the source.

There should be a whole variety of distances between microphones. The greater the variety of intervals between sensors, the more frequencies can be treated and the more phase angles can be accounted for.